All-Optical flip-flop operation using a SOA and DFB laser diode optical feedback combination

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Abstract: We report on the switching of an all-optical flip-flop consisting of a semiconductor optical amplifier (SOA) and a distributed feedback laser diode (DFB), bidirectionally coupled to each other. Both simulation and experimental results are presented. Switching times as low as 50ps, minimal required switch pulse energies below 1pJ and a repetition rate of 1.25GHz have been measured. Contrast ratios over 25dB have been obtained. The dependence on the pulse length and CW input power of the minimal required switch energy is investigated.

OCIS codes: (130.4310) nonlinear; (130.5990) semiconductor; (190.0190) bistability; (230.4320) nonlinear optical devices.

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1. Introduction

All-Optical packet switched networks have been proposed as the future telecommunication networks able to cope with the massive bandwidth requirements resulting from the huge growth of the Internet and its services [1], [2]. Because the datastream in these networks is divided in individual packets on which a header (usually with a lower bitrate) is attached and because only the header is processed in the intermediate nodes these networks can be data format and bitrate transparent. Furthermore a high transmission efficiency and high data rate operation can be obtained. Also worth to mention is the low footprint of an all-optical node as compared to an electro-optical node.

One of the key components in packet switched all-optical networks is the all-optical flip-flop, which makes it possible to switch the packet to a different (wavelength) channel depending on the header of the packet [3]. The all-optical flip-flop is switched or not depending on the result of the processing of the header in the node. The output power from the flip-flop is thereby typically used as CW input signal for a wavelength converter and the delayed packet information can then be wavelength converted.

Over time different all-optical flip-flops have been proposed such as devices based on multimode interference bistable laser diodes [4], coupled laser diodes [5] or coupled Mach-Zehnder interferometers [6], [7]. The reported switching times of these devices are typically a couple of hundred ps, while the energy of the set and reset pulses required to switch the device is usually a couple of pJ.

Here we numerically and experimentally demonstrate and discuss an all-optical flip-flop (AOFF) composed of a semiconductor optical amplifier (SOA) and a DFB-laser diode mutually connected through a coupler [8], [9], [10]. We show that the device can operate for different input wavelengths, pulse lengths and CW input powers making it a very flexible and robust device usable for different network conditions. Contrast ratios as high as 25dB, set and reset pulse lengths of 50ps and set and reset pulse energies of below 1pJ have been obtained. Switch times of around 50ps were measured. Fast switching of the all-optical flip-flop at 1.25GHz is shown making the device usable as a reconfigurable switch.

A description of the device and the principle of operation will be given in section 2. In section 3 simulation results, both static and dynamic, will be presented. Experimental results as well as a comparison between simulation and experimental results will be shown in section 4.

2. Device description

The device under consideration here is an integrated feedback scheme consisting of a semiconductor optical amplifier mutually optically coupled to a DFB laser diode by means of a (possibly variable) coupler. A schematic representation of the device is given in Fig. 1.

When a CW signal is injected into the SOA (port 1) the optical feedback between this signal and the laser light from the DFB laser diode can lead, for a certain range of input powers, to an optical bistable domain. Inside the bistable domain, one of the stable states is with the laser diode operating above threshold and with the laser power saturating the SOA and suppressing the injected signal. The other stable state is with the laser diode switched off by the amplified injected signal and with larger amplification for the injected signal.

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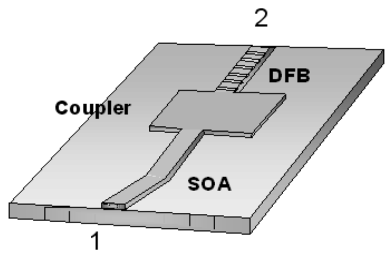

Fig. 1. Schematic of a SOA bi-directionally coupled to a laser diode

By applying a CW input signal chosen inside the bistable domain the device can be used as an all-optical flip-flop by applying optical set and reset pulses to make the device switch between the 2 stable states present. When the device is in the OFF-state a set pulse is injected into the laser diode (port 2) and normally causes the laser diode to switch back on. This is due to the fact that the optical pulse, after passing through the laser diode, leads to an increase in the total power injected into the SOA and thereby decreases the gain for the (CW) input signal. This causes less SOA output power to be injected into the laser diode giving the laser diode the chance to switch back on. When the device is in the ON-state a reset pulse is injected at the SOA side (port 1), which increases the output power of the SOA and therefore also the power injected into the laser diode, which in turn can cause the laser diode to switch off.

3. Simulation results

The SOA/DFB-laser diode feedback scheme was first numerically investigated using a commercial software package [11]. The setup used in the simulations is shown in Fig. 2. A 500μm long SOA is connected through a bidirectional 3dB coupler with a 350μm long quarter wave shifted DFB laser diode. In the results shown below the wavelength of the laser output power is 1553nm and the signal wavelength is 1538nm. The signal wavelength can be varied as long as it is sufficiently distant from the Bragg wavelength of the DFB laser diode. The optical pulses used for the switching of the device are first order Gaussian pulses (with a certain full width half maximum (FWHM) and peak power). A CW input power is injected into the SOA and the optical set and reset pulses can be injected at port 2 and port 1 respectively. Alternatively they can also be injected at port 4 and port 3 (at the coupler). In this way the propagation of the pulse through the SOA (reset pulse) and DFB-laser diode (set pulse) can be avoided.

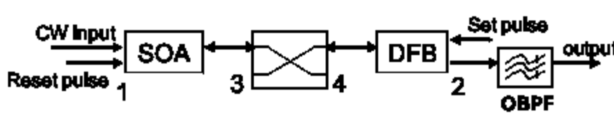

Fig. 2. Schematic setup used for the simulations

In Fig. 3 a static response of the output of the laser diode as a function of the CW input power injected into the SOA is shown. The drive currents are 120mA for the SOA and 100mA for the laser diode. As long as the input power to the SOA remains below -5dBm the influence of the fraction of the output power of the SOA injected into the laser diode is limited and the output power of the laser diode remains high. For input powers between about -5dBm and 2dBm a bistable domain of about 7dB wide and a contrast ratio of over 25dB between the two stable states can be observed. In this bistable region the actual state of the device is determined by

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the history of the device. As long as the output power of the laser diode doesn't get influenced much by the amplified input power coming from the SOA the laser output power remains high. Due to the suppression of the gain in the SOA the amplification of the input power can remain low in that case. For the lower branch of the bistable domain a decrease in input power results in only a small decrease in the output power of the SOA keeping the laser diode switched off. When the input power decreases below a certain value (in this case about -5dBm) the fraction of the output power of the SOA injected into the laser diode becomes low enough to allow the laser diode to switch on again.

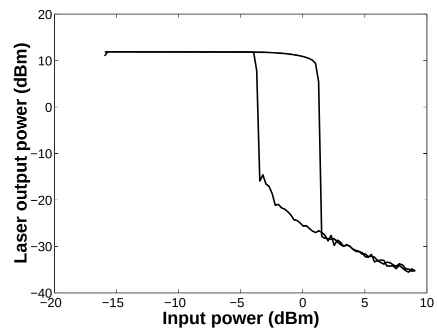

Fig. 3. Static bistable transfer function of the all-optical flip-flop

When injecting a constant power, chosen inside the bistable domain, of for example -0.5dBm into the SOA the device can be switched, as shown in Fig. 4, by using optical set and reset pulses. The FWHM of the pulses is 50ps and the minimal required peak power is 47 and 90mW for the set and reset pulses respectively. This results in a minimal required pulse energy of 870fJ for the set and 1.7pJ for the reset pulse. The set pulse temporarily depletes the gain of the SOA, thereby causing a decrease in the amplification of the CW input power. This gives the laser diode the opportunity to switch on. The reset pulse acts as an extra input power into the SOA, increasing the power injected into the laser diode and causing the laser diode to switch off.

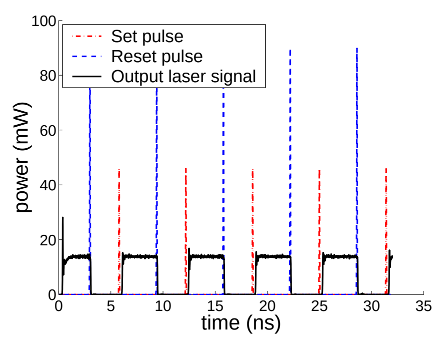

Fig. 4. All-optical flip-flop operation of the device for 50ps set and reset pulses with a respective pulse energy of 870fJ and 1.7pJ.

In Fig. 5 the set and reset pulse energies are shown as a function of the pulse length for different CW input powers to the SOA. Ideally the energy required to switch the device between the two stable states is the same for the set and reset operation. This holds best for CW input powers chosen in the center of the bistable domain. When shifting the CW input power towards one of the edges of the bistable domain a growing asymmetry between the set and reset pulses can be

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observed. It can be noted that when the SOA input power moves towards the left boundary of the bistable domain in Fig. 3 the set pulse energy becomes lower while the reset pulse energy rises. The contrary holds when the CW input power nears the right boundary of the bistable domain.

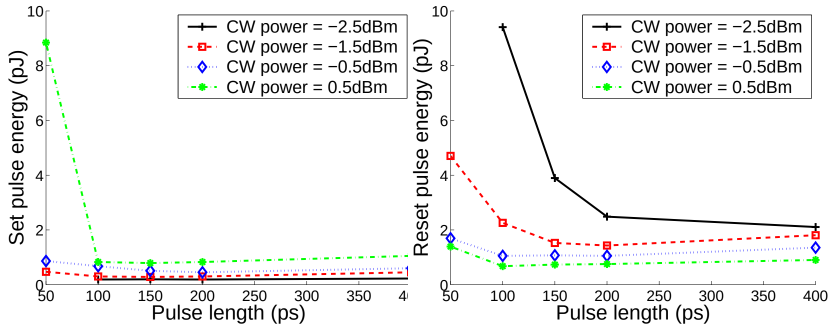

Fig. 5. Minimal required set (left) and reset (right) pulse energies for all-optical flip-flop operation as a function of pulse length and CW input power.

From Fig. 5 it can also be seen that the pulse energy rises with decreasing pulse length. Due to the optical feedback present between the SOA and the DFB laser diode, the effect of a set or reset pulse needs to be long enough to enable the feedback to switch the state of both the SOA and the DFB laser diode. As the set and reset pulses essentially lead to a carrier depletion in the SOA (set) or DFB laser diode (reset) it is clear that shorter pulses need to deplete the carriers more in order to make the deviation from the original state last longer.

4. Experimental results

4.1. Setup

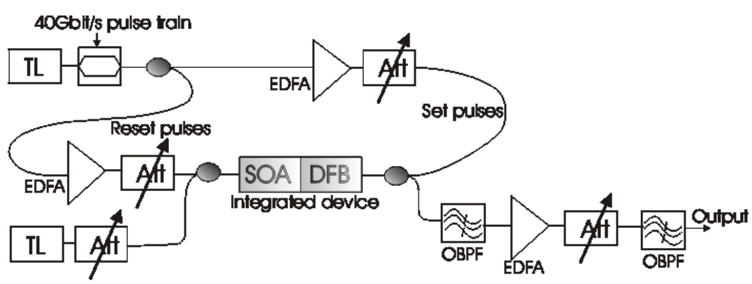

Fig. 6. Experimental setup used for the measurements of the SOA/DFB laser diode based AOFF.

The experimental setup used for the demonstration of all-optical flip-flop operation is shown in Fig. 6. To provide and control the constant input power into the SOA, needed to make the device operate inside the bistable domain, a wavelength tunable laser is used that is followed by an attenuator. The set and reset pulse trains are generated using another wavelength tunable laser and a 40Gbit/s NRZ-bit pattern generator that drives an electro-optical modulator. After generation of the pulses, they are split using a 3dB coupler giving identical set and reset pulses. Using an EDFA and an attenuator for both the set and reset pulses the power of the pulses can be varied. The delay between the set and reset pulse train was obtained by using an optical fiber

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delay line along one of the paths. By changing the length of the delay line the delay could be varied. At the SOA side a 3dB coupler is used to combine the CW input power and the reset pulse train, while at the DFB laser diode side a coupler is used to inject the set pulse train and to extract the output power of the laser diode. An optical bandpass filter is used to separate the laser output power from the CW power.

The device used is an integrated version of the feedback scheme consisting of a SOA connected to a DFB-laser diode array through a 1X4-coupler. The coupling ratio between the SOA and each DFB-laser diode is then 25%. The fiber to chip coupling is done by means of lensed fibers.

4.2. *Results*

The static response of the laser output power as a function of the input power into the SOA for different wavelengths of that input power is shown in Fig. 7. The drive current of the SOA is 103.5mA and the drive current of the laser diode is 101.4mA. The wavelength of the laser signal is 1538.7nm. Unless otherwise stated these operating conditions apply for all the following results.

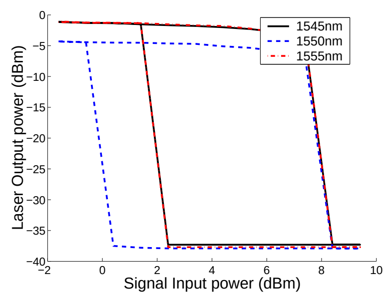

Fig. 7. Laser output power as a function of input power into the SOA for different wavelengths of the input signal

For the outer wavelengths (1545nm and 1555nm) the width of the bistable domain is about 6dB while for an input signal at 1550nm it is 2dB wider. This might be explained in part by the wavelength dependence of the SOA gain (with the gain peak around 1550nm) and the difference in coupling ratio between the SOA and DFB-laser diode for different wavelengths. The contrast ratio in the bistable domain is over 35dB.

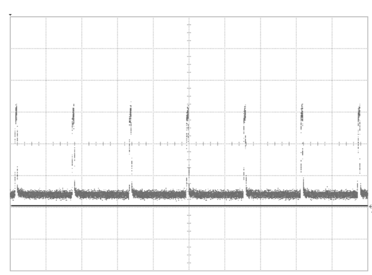

Fig. 8. Pulse train of 100ps wide pulses with a pulse spacing of 1.6ns

From Fig. 7 it can be seen that the CW input power can be chosen anywhere between 2.5 and 7.5dBm. Because of the CW power present in the generated pulse train, as can be seen in Fig. 8, however the actual part of the bistable domain to be used is smaller. This CW component

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causes the total CW power injected into the SOA to rise, causing the working point inside the bistable domain to shift to higher CW input powers.

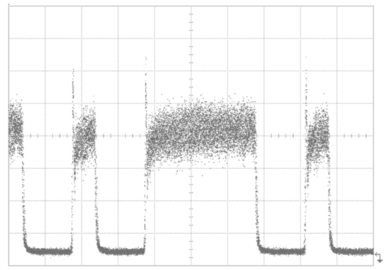

Fig. 9. Dynamic flip-flop operation for 150ps set and reset pulses and a CW input power of 6.4dBm (1ns/div).

An example of all-optical flip-flop operation of the SOA/DFB laser-diode feedback scheme is shown in Fig. 9. The set and reset pulses are 150ps long and the wavelength of the CW input power and the pulses is 1555nm. The set pulse energy is 10.6pJ and the reset pulse energy is 4.4pJ. The contrast ratio between the ON-state and the OFF-state of 11.6dB is lower then expected from Fig. 7 but might be explained by the limited sensitivity of the receiver resulting in an overestimation of the zero level (due to the shot noise of the receiver). The repetition rate (defined as the rate at which two equal transitions (being on to off or off to on occur)) is as high as 500MHz here.

The set and reset switch time of the AOFF is in this case as low as 150ps as can be seen in Fig. 10. The transient in the switch on of the AOFF is caused by the relaxation oscillation of the DFB laser diode.

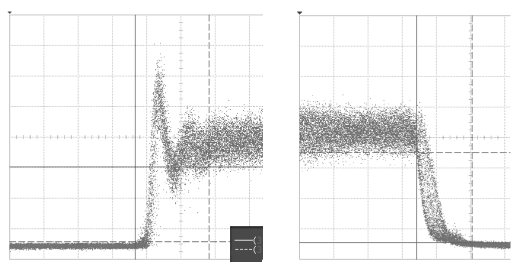

Fig. 10. Set and reset switch times for 150ps set and reset pulses and a CW input power of 6.4dBm (100ps/div).

In Fig. 11 the evolution of the minimal set and reset pulse energy required to perform switching of the all-optical flip-flop as a function of pulse length (between 150ps and 400ps) and for different CW input powers situated inside the bistable domain is shown. The wavelength of the CW input power and the set and reset pulses is in this case 1555nm. Minimal set and reset pulse energies of below 5pJ can be observed albeit not for the same CW input power. The minimal required set pulse energy to switch the AOFF on rises for a fixed pulse length with increasing CW input power, which corresponds to the numerical results shown in Fig. 5. At the same time the minimal required reset pulse energy to switch the AOFF off decreases with increasing CW input power for fixed pulse lengths. The same dependence of the set and reset pulse energy on the pulse length and CW input power could be found for the other 2 static bistable domains (for a wavelength of 1545 and 1550nm for the CW input power and for the pulse trains) shown in

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Fig. 7.

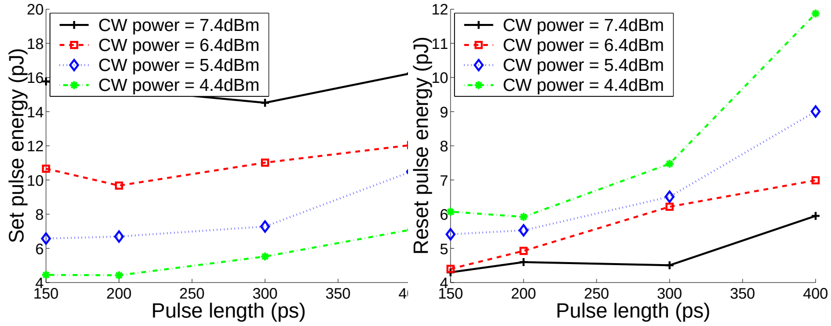

Fig. 11. Minimal required set (left) and reset (right) pulse energies for all-optical flip-flop operation as a function of pulse length and CW input power for a CW input power and pulse wavelength of 1555nm.

The increase of the required reset pulse energy for increasing pulse length may be caused by the decrease of the CW component in the reset pulse train when the pulse length grows longer (as a result of the use of an EDFA for the amplification of the pulses the average power is kept constant but by increasing the pulse length the duty cycle of the signal changes thereby actually decreasing the amplification of the CW component). Due to the decrease of this CW component the operating point of the all-optical flip-flop inside the bistable domain shifts towards the left edge of the domain resulting in a higher pulse power required to switch the AOFF. The energy of the set pulses remains almost equal, corresponding with the simulation results obtained in Fig. 5.

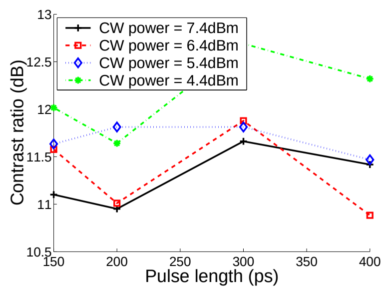

Fig. 12. Contrast ratio between the ON and OFF state of the AOFF as a function of pulse length and CW input power for a CW input power and pulse wavelength of 1555nm.

Figure 12 shows that the contrast ratio between the ON and OFF state of the AOFF varies over less then 2dB for different pulse lengths and CW input powers.

Using a different electro-optical modulator, which allowed us to suppress the CW component present in the generated set and reset pulse trains all-optical flip-flop operation using set and reset pulses as short as 50ps has been obtained. The drive current was 105.8mA for the laser diode and 83mA for the SOA. The wavelength of the input signal and the set and reset pulses is 1550nm.

Figure 13 shows the dynamic AOFF operation of the device for 50ps long optical set and reset pulses and a CW input power of 4.5dBm. The energy of a set and reset pulse is respectively 1.6pJ and 0.9pJ. The contrast ratio between the two states of the AOFF is measured to be 19dB. The repetition rate here is as high as 1.25GHz.

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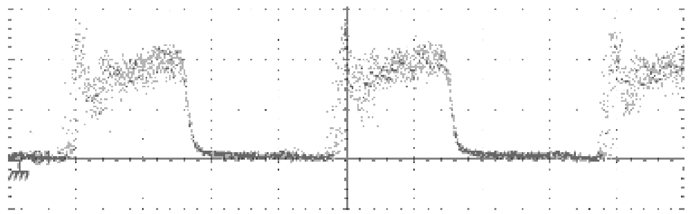

Fig. 13. Dynamic AOFF operation with set and reset pulses of 50ps long and a CW input power of 4.5dBm (200ps/div).

The reason for the lower set and reset pulse energies here as compared to results presented higher can be found in the reduction of the CW component present in the set and reset pulse trains. When a CW component is present in the reset pulse train this causes the device to shift to the right boundary of the bistable domain. This results in a higher required set pulse power for the device. But the CW component in the set pulse train also causes a disturbance away from the ideal state where no extra CW component is present resulting in a decreased influence of the reset pulses. This is due to the fact that the CW component present in the set pulse train after passing through the laser diode slightly counteracts the switch of the carrier distribution in the SOA during the switch off operation of the AOFF. The interplay between the 2 CW components leads to a higher requires set and reset pulse energy then would be the case without or with a lower CW component present in the pulse trains.

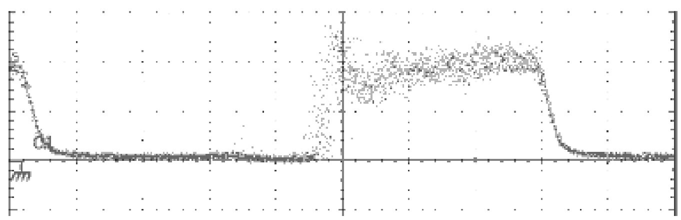

Fig. 14. Dynamic AOFF operation with set and reset pulses of 50ps long and a CW input power of 4.5dBm (100ps/div).

In Fig. 14 the rise and fall time of the AOFF can be observed as being around 50ps resulting in very fast switching between the two states. Our measurements showed that the rise and fall time of the AOFF decreases with decreasing pulse length of the set and reset pulses. By using shorter pulses the switching time of the device may be further reduced.

Very low switching energy operation, as can be seen in Fig. 15, has been obtained as well, with pulse energies as low as 0.7pJ and 0.9pJ for 100ps long set and reset pulses respectively. The contrast ratio is here over 25dB and the repetition rate is again 1.25GHz making the device suitable for very fast, low energy switching operations.

5. Conclusions

We showed both by simulations and experimentally that a device consisting of a SOA and a DFB-laser diode in an optical feedback configuration can be used as an all-optical flip-flop. Dynamic operation of the device has been demonstrated for different CW input powers chosen inside the bistable domain, making the control of this CW input power less critical for good operation of the device. Given the response of the device to different input wavelengths we can conclude that a single CW laser can be used to provide the CW input power to different AOFF's based on this concept combined in a complete all-optical packet switch. It was shown that the

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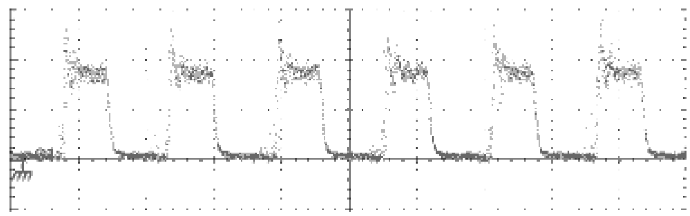

Fig. 15. Dynamic AOFF operation with set and reset pulses of 100ps long and a CW input power of 3.5dBm (500ps/div).

CW input power could be varied over 3dB while the wavelength could be changed over at least 10nm while still maintaining AOFF operation.

The device also operates for different set and reset pulse lengths, ranging from 50ps to 400ps. The switching time (both rise and fall time) can be as low as 50ps, while a repetition rate of 1.25GHz has been measured making the device suitable for fast switch operations. The lowest required set and reset pulse energies to come to AOFF operation were 0.7pJ and 0.9pJ respectively.

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